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Abstract

All the information necessary to achieve reasonably efficient coupling of semiconductor lasers to single mode fibers is collected from the literature, reworked when necessary, and presented in a mostly tabular form. Formulas for determining the laser waist radius and the fiber mode radius are given. Imaging relations connecting these values with the object and image distances are given for three types of lenses: ball, hemisphere, and GRIN. Sources for these lenses are indicated, and a brief discussion is also given about ways of reducing feedback effects.

LASER TO SINGLE-MODE-FIBER COUPLING: A LABORATORY GUIDE

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A common need in many laboratories is the coupling of the output of a semiconductor laser into a single mode fiber. While there are many papers which deal with various aspects of this problem, there does not seem to be a convenient reference where one can obtain all the information needed to accomplish this task. The present paper has been written in an attempt to satisfy this need for the interested worker.

The coupling problem in general consists of aligning the laser and the fiber, together with some optical element, in such a way as to obtain the maximum power transfer between the two systems. Usually, this step has to be followed by a means of permanently locking these elements into a fixed position, but the present paper does not address this issue, laboratory or optical bench methods being those mainly considered.

In principle(1), the correct procedure can deliver coupling efficiencies approaching 100%. This results if the laser mode and the fiber mode are made to have the same form, and to overlap in the same region of space. In practice, achieving such high efficiencies is quite involved, requiring aberration corrected and antireflection coated lenses. Other difficulties arise if the laser beam is strongly elliptic. The position taken in this paper is that most workers will be satisfied with lower efficiencies, on the order of 40% or 50%. Such values are achievable in single lens systems, which possess a further advantage in that Fresnel reflection losses are often tolerable, so that antireflection coatings are not required. However, single lens systems cannot deal adequately with lasers having extremely elliptic beams, leading to reduced efficiencies in such cases. Other problems not addressed in this paper are laser astigmatism, mainly because currently popular lasers are of the index-guided type where this problem is not serious, and the displacement of the laser waist away from the laser facet, because this can be compensated for by a slight adjustment away from the calculated optimum position. In any case, it is common procedure to use calculations such as those described in this paper to determine what optical element to use and where to position it, and then to maximize coupling efficiency by further small adjustments in positions.

The content of this paper is arranged in the following way: after a few words on laser beams, a table is provided which allows the calculation of the laser beam waist radius, in other words the laser mode size. A formula is next displayed, which can be used to obtain the fiber mode size. The conversion of the

laser mode into a fiber mode is then handled by means of a rearrangement of the formulas given by Kogelnik(2) and by Self(3), which yield the object and image distances for a particular lens which carries out this conversion. Before using these formulas it is necessary to decide on the lens type, and then look up the focal length and the thick-lens correction terms in table II, and insert them into the equations. This table covers three types of optical elements: the spherical ball lens, the hemispherical lens, and the GRIN lens. Both ball lenses and GRIN lenses can be obtained commercially, but the hemispherical lens is usually fabricated in the laboratory. A fabrication procedure is indicated, and sources are given for obtaining ball and GRIN lenses. The paper concludes with a discussion of ways of reducing feedback, as this can cause serious difficulties in many experiments.

Laser Beams

In all that follows it will be assumed that the laser emits a Gaussian beam. From the knowledge of the beam angle it is possible to estimate the dimension of the laser beam near the exit aperture of the laser, i.e. near the laser facet. The laser beam angle is sometimes specified by the manufacturer, but more often than not it must be measured. For this purpose one needs a photodetector provided with an entrance slit, and some means of rotating the laser in two perpendicular planes, in front of the slit. The diameter of the beam near the laser facet will be taken to be the beam waist, i.e. the minimum diameter of the laser beam. However, following common practice, formulas given below use the waist radius rather than the diameter. Table I may be helpful in converting each of three common beam angle definitions into the laser beam waist radius.

The definition of waist radius in the table and in the rest of the paper is based on the $1/e^2$ value, and the units are those used to express the wavelength. If the laser beam is not circular one obtains two waist radii, one for each semi-axis of the ellipse. If these values are not too different, one can proceed by calculating their geometric mean $(w_a w_b)^{1/2}$ and use this number in the formulas requiring an entry for the laser waist radius. A ratio of 3:1 is perhaps acceptable, but higher ratios make it difficult to obtain adequate coupling efficiency without some means of circularization.

Fiber Mode Radius

The mode propagating in the fiber can also be approximated by a Gaussian beam, and described through a mode radius w_f . This mode radius is slightly larger than the single mode fiber core radius a , because of the spreading of the mode into the cladding region.

The equation of Marcuse(4) can be used to estimate this spreading

$$\frac{w_f}{a} = 0.65 + \frac{1.619}{V^{1.5}} + \frac{2.879}{V^6} \quad (1)$$

where

$$V = \sqrt{\frac{2\pi}{\lambda} a (n_1^2 - n_2^2)} \quad (2)$$

with n_1 the core index and n_2 the cladding index. The fiber mode radius can sometimes be obtained directly from the manufacturer. One often finds that $w_f/a \approx 1.1$.

Imaging formulas

An unspecified optical element is defined by the focal length f , an entry surface, an exit surface, and two principal planes, as shown in figure 1.

The desired object distance s_o and image distance s_i are distances from the object to the entry surface and from the exit surface to the image, respectively, as shown in the figure, while Δ and Δ' , the thick-lens correction factors, are distances between the entry surface and the entry principal plane and the exit surface and the exit principal plane, respectively. We deal with the case of a real object and real image, so that all quantities are taken as positive. It can then be shown that

$$s_o = f - \Delta + f \sqrt{\left[\frac{w_l}{w_f} \right]^2 - \left[\frac{z_R}{f} \right]^2} \quad (3)$$

$$s_i = f - \Delta' + \left[\frac{w_f}{w_l} \right]^2 (s_o + \Delta - f) \quad (4)$$

where $z_R = \pi w_l^2 / \lambda$. Before using these equations, it is necessary to choose one of three optical elements, and consult Table II for the appropriate expression for f , Δ , and Δ' .

Comments

Ball lens

A variety of materials are available from Deltronics Crystal Industries (5) in diameters ranging from 0.4 to 3 mm. A list of materials from one of their catalogues is given below:

Material	Refractive Index at 0.80 μm
Sapphire	1.75
YAG	1.824
GGG	1.953
CZ	2.135
YIG	2.25
Si	3.505

Some of these spheres need to be coated with an antireflection film since the two-surface Fresnel loss (for a flat surface) varies from 15 percent to 62 percent.

Hemispherical lens

The most useful case arises when the lens is directly attached to the fiber. One can then substitute $s_1 = 0$ in equation 2, which leads to

$$R = \frac{(n-1) z_R}{\sqrt{\left[\frac{w_l}{w_f}\right]^2 - \frac{1}{n^2} \left[\frac{w_l}{w_f}\right]^4}} \quad (5)$$

$$s_o = \frac{R}{n-1} \left\{ 1 - \frac{1}{n} \left[\frac{w_l}{w_f}\right]^2 \right\} \quad (6)$$

In this case the lens diameter is restricted to a particular value for a given index, and there is only a single value for the laser to lens distance. The maximum acceptance half angle α for the hemispherical lens on end of fiber is given by

$$\alpha \sim \tan^{-1} \left\{ \frac{w_l}{s_o} \sqrt{1 + \left[\frac{s_o}{z_R}\right]^2} \right\} \quad (7)$$

A convenient way of making such a lens has been described by Izadpanah and Reith (6). The fiber is etched in HF placed in a teflon beaker, with a thin layer of oil floating on top of the HF.

After etching to the desired diameter, the lens is formed by heating in a fusion splicer. The refractive index of the lens may be approximated by the index of the core, if the diameter is small, or otherwise by the index of the cladding material.

GRIN lens:

The grading parameter b is defined by the expression $n = n_o[1 - 2r^2/b^2]$. Other often used expressions are $n = n_o[1 - g^2r^2/2]$, giving $b = 2/g$, and $n = n_o[1 - Ar^2/2]$, giving $6b = 2/\sqrt{A}$.

Melles Griot(7) carries a selection of these, and they can also be obtained from the manufacturers, NSG(8). The standard version discussed here has flat end faces. NSG also sells antireflection coated units with curved input surfaces for aberration correction.

Feedback

Reflection back into the laser is undesirable as it affects the laser wavelength, stability and noise. For critical applications it will be necessary to use isolators, while for others one can use antireflection coated optics. The most critical surface is the first surface facing the laser, and it is often sufficient to make that spherical. An uncoated hemispherical lens with a $145 \mu\text{m}$ diameter, on the end of a fiber, has been reported to display a reflectivity of 10^{-5} - 10^{-6} (9). Yet another approach to reducing feedback from the first surface is to grind the end of the fiber into a wedge. Although this method has been proposed for coupling into multimode fibers (10), workers at NASA Langley Research Center (Terry Mack, unpublished data) have obtained coupling efficiencies as high as 18% into wedged single mode fibers.

An estimate for the desired wedge angle can be obtained as follows:

Starting with the solution for the hemispherical lens on the end of the fiber, one approximates the circular profile by two straight line segments, as shown in figure (2).

The wedge angle β is then given by

$$\beta = 90^\circ - \frac{1}{2} \sin^{-1} \left[\frac{w_f}{R} \right] \quad (8)$$

where R is obtained from eq.(5). For the beam waist radius needed in eq.(5) one uses the smaller of the two laser waists, with the fiber wedge oriented so as to intercept this wider beam. Grinding the fiber can be done by pressing the free-standing end into the disk of a lapping and polishing machine, and then repeating the procedure after rotating the fiber through 180 degrees.

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Table I: Beam angle and beam waist radius

Definition of Beam Angle θ in degrees	Waist radius w_1 near laser facet, in same units as λ
Full width to half maximum intensity(FWHM)	$21.5 \lambda/\theta$
Half width to $1/e$ times maximum intensity	$12.9 \lambda/\theta$
Half width to $1/e^2$ times maximum intensity	$18.24 \lambda/\theta$

Table II: Imaging formula parameters

Type of lens	f	Δ	Δ'
Ball, radius R index n	$\frac{nR}{2(n-1)}$	R	R
Hemispherical, radius R , index n	$\frac{R}{n-1}$	0	$\frac{R}{n}$
GRIN, length l , diameter D , axial index n_o , grade b	$\frac{b}{2n_o \sin \frac{2l}{b}}$	$\frac{b}{2n_o} \tan \frac{l}{b}$	$\frac{b}{2n_o} \tan \frac{l}{b}$

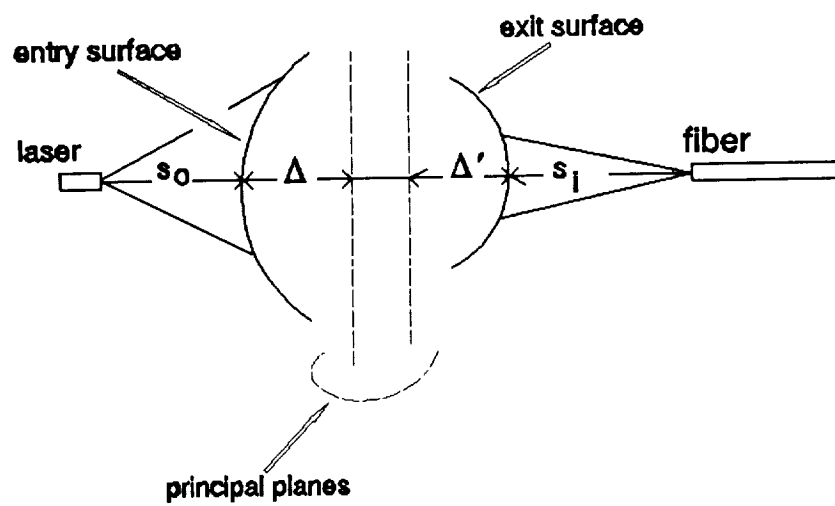


Figure 1: Coupling geometry.

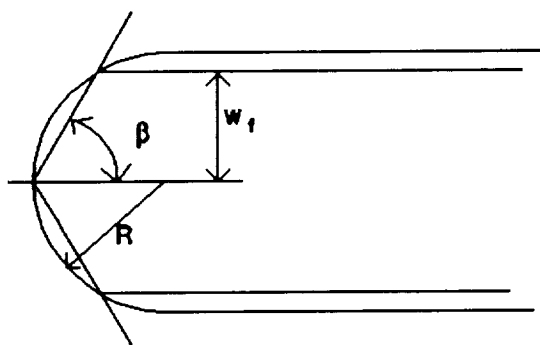


Figure 2: Approximation to the wedge.

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